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**REVIEW PAPER**

# METHODS FOR ENRICHMENT OF ANIMAL DIETS WITH SELENIUM

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### Abstract

Selenium is considered to be an element essential for the proper functioning of animal and human organisms. Its most important functions include anticancerogenic activity and beneficial effects on the human circulatory system, as well as its role during the perinatal period in animals. This article discusses a significant role selenium plays in animal organisms, the soil content of this element in soils, and a prospect for Se enrichment in plants to levels covering the dietary needs of animals. The incidence of selenium deficiency in animals can be reduced by enriching fodder with supplements containing selenium in mineral compounds, which are much less assimilated by living organisms than its organic forms. The paper also provides information on the content and bioavailability of selenium in Polish soils and presents the average concentrations of this element in different species of plants. While the methods of introducing selenium into the soil-plant-animal-human food chain have been extensively studied during the recent years, the practice of fertilizing plants with this element is still less known. The basic source of selenium for plants is soil, yet most of the soils in Poland are poor in selenium. It has been demonstrated that the application of 5 to 10 g $ha^{-1}$ Se in the cultivation of cereals, meadows and pastures may increase its content in plants to the level covering the needs of animals for this element. The effectiveness of Se enrichment in plants to a level safe in animal nutrition may depend not only on the dose or chemical form of selenium applied, but also on the species and varietal properties of plants, the time of application and the application method itself. Due to a small difference between the optimal and toxic content, plant fertilization with selenium should be preceded by a study on its content in soil, as well as the ability of plants to accumulate this element.

**Keywords**: selenium in plants and animals, soil, fertilizers, biofortification.

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# INTRODUCTION

The first report on the beneficial effects of selenium on the animal organism appeared as early as in 1941, when Poley et al. (1941) demonstrated faster growth of chicks fed with fodder containing 2 mg Se $kg^{-1}$. In 1957, Swarz and Foltz (1957) showed that this element prevented liver necrosis in rats. In 1973, the discovery that selenium was present in the enzyme glutathione peroxidase, involved in the reduction of cytotoxic peroxides in many metabolic pathways (Rotruck et al. 1973, Lyons et al. 2007, Suchý et al. 2014), initiated further research on the function of this element in animal and human organisms, including its presence in the structures of 30 various proteins, relation with vitamin E and sulfur amino acids (Rotruck et al. 1973).

Malagoli et al. (2015) estimate that the problem of selenium deficiency affects 800 million people worldwide. This is caused by the low abundance of this element in soils, and its limited bioavailability for plants (Hartikainen 2005, White, Broadley 2009, White 2016). Depletion of the soil pool of selenium, resulting especially from intensive plant cultivation, may contribute to aggravation of selenium deficit unless measures are taken to incorporate this element into the soil-plant-animal-human food chain. A posible way to counteract Se deficiency is the enrichment of crops with selenium. Plant biofortification is currently used in countries such as Australia, the USA, New Zealand, the United Kingdom or Finland, where legal regulations on the obligatory enrichment of mineral fertilizers with selenium have been passed (Alfthan et al. 2015). In this context, the Finnish government is a pioneer in the application of inorganic Se fertilizer in a biofortification programme (Broadley et al. 2010). Relatively little attention given to this problem in Poland results from the lack of available literature dealing with this issue, and from technical and economic reasons. Importantly, the essential role of selenium in living organisms necessitates the incorporation of this element into soil through fertilization.

Below, we review the functions of selenium in animal organisms, and the content of this element in soils, with a special focus on the prospect for Se enrichment in plants to levels covering the dietary needs of animals.

## ROLE OF SELENIUM IN ANIMAL HEALTH AND NUTRITION

The identification of selenium in the structure of glutathione peroxidase (GPX) led to a better understanding of its function in animal and human organisms. The GPX enzyme is involved in the conversion of highly toxic peroxides into less biologically reactive forms, thus protecting the components of cell membranes from the negative effects of oxidation (Żarczyńska et al. 2012, Moeini, Jalilian 2014, Sobiech et al. 2015, Żarczyńska et al. 2017). Its antioxidant properties and modulation of the transcription factors result in the inhibition of tumor cell proliferation. In areas with the low selenium quantities in soils and, consequently, lower Se concentrations in plant products, there is a higher incidence of the breast, skin, lung, bladder, ovary and uterus cancers (KARWACKA et al. 2014). In fact, selenium is even more effective as an antioxidant when combined with vitamin E, as both compounds cooperate inhibiting peroxidation of polyunsaturated fatty acids (ZUBAIR et al. 2015).

In mammals, selenium occurs in two amino acids, selenocysteine and selenomethionine, contained in polypeptides called selenoproteins. The most important selenoproteins include thioredoxin reductase (TrxR) protecting endothelial cells, selenoprotein W (SEPW1) involved in the transport of selenium, and iodothyronine deiodinase increasing thermogenesis and metabolic rate (MOEINI, JALILIAN 2014).

The difference between selenium deficiency, its optimal content, and the amount dangerous to animal health is small. The toxic effect of selenium is multimodal, mainly due to its competition with sulfur in various biologically active compounds. Selenosis (caused by excessive consumption of this element) induces anaemia, myocardial atrophy, limb stiffness and blindness (KARWACKA et al. 2014).

It has been shown in many studies that selenium applied in an amount optimal for a specific species has a positive effect on health, namely it can reduce heart arrhythmias and the incidence of myocardial infarctions, improve systolic relaxation and increase cardiovascular tolerance to ischaemic damage (OŠŤÁDALOVÁ 2012). One of the most thoroughly investigated diseases caused by selenium deficiency is nutritional muscular dystrophy (NMD) or white muscle disease, which most often occurs in animals less than 6 months old, mainly in calves and lambs. NMD may attack the thigh muscles or the tongue, and its typical symptoms are: incorrect posture, humped spine, difficulties in sucking, swallowing and withdrawal of milk through the nostrils. In acute conditions, nutritional muscular dystrophy may lead to the death of an animal (RADWIŃSKA, ŻARCZYŃSKA 2014). Selenium deficiency in animals may also cause clinical symptoms such as reduced appetite, inhibition of growth, productivity and fertility, increased risk of embryonic death and miscarriage, placental retention, ovarian cysts, and uteritis in dairy cows, as well as impaired spermatogenesis in cattle and sheep (KHANAL, KNIGHT 2010). As reported by CHOCT and NAYLOR (2004), diseases such as exudative diathesis and pancreatic fibrosis in poultry, liver necrosis and heart disease in pigs, and white muscular disease in sheep can be effectively avoided by supplementing the diet with selenium. ENJALBERT et al. (2006) found that a low selenium content in the feed supplied to mothers during pregnancy reduces the immunity of neonatal calves, and affects the iodine metabolism in cattle, which in turn may increase the perinatal mortality rate and result in the retarded growth of young animals.

Selenium may also affect the quality of animal meat, reducing water loss, improving colour stability, providing protection against oxidation, and thus increasing its shelf life (Joksimović Todorović et al. 2012).

The dietary requirements for selenium in animals depend on many factors, e.g. the species, age, role in food production. Based on the literature, Zimoch and Patorczyk-Pytlik (2011) concluded that the optimum content of selenium in the feed varies from 0.10 to 0.30 mg Se $kg^{-1}$ DM for cattle, 0.15 to 0.35 mg Se $kg^{-1}$ DM for pigs, and 0.10 to 0.20 mg Se $kg^{-1}$ DM. for poultry, sheep and horses. However, a higher demand for selenium among cattle is demonstrated by dairy cows and heifers, and among pigs – by piglets, weaners and sows (0.30-0.35 mg Se $kg^{-1}$ DM), which is related to the function of selenium in the perinatal period of these animals. On the other hand, Khanal and Knight (2010), referring to the WHO data, stated that, provided an appropriate level of vitamin E, the optimum dose of selenium for most species is 0.04-0.10 mg $kg^{-1}$ DM fodder, for poultry 0.15-0.20 mg $kg^{-1}$, in pigs 0.03-0.05 mg $kg^{-1}$, and in cattle 0.10-0.18 mg $kg^{-1}$.

The effectiveness and bioavailability of selenium for an animal organism are determined by a dose and a chemical form in which the element is administered. Sodium selenate (IV) is not highly biologically active, in addition to which it accelerates the oxidation processes in an organism and may cause health problems. In contrast, organic forms of selenium are more active and play a key role in biological processes. These organic forms include selenomethionine (Se-Met) and selenocysteine (Se-Cys), characterized by higher bioavailability for organisms than inorganic compounds (Choct, Naylor 2004, Suchý et al. 2014). Furthermore, the toxicity of selenium in the organic form is estimated to be at least three times lower (Choct, Naylor 2004, Erdoğan et al. 2017). Selenium in fodder is mainly present in the form of L-selenomethionine, which is its natural form in plants and in animal tissues (Rovers 2014).

## METHODS OF SUPPLYING SELENIUM TO ANIMALS

Selenium can be delivered to animals in two ways: directly by supplying selenium yeast or mineral compounds (injectable, oral and intraruminal), or indirectly by enriching fodder plants (Dębski 1992). In intensive livestock production, selenium deficiencies are compensated by the addition of this element to mixed feeds with a premix in amounts depending on a species, age and productivity of animals. It is added to feeds in quantities varying from 0.10 to 0.30 mg Se $kg^{-1}$ in the form of sodium (IV) or (VI) selenate. The maximum content of selenium in a mixed feed for all animal species was reported to range from 0.30 mg Se $kg^{-1}$ (Erdoğan et al. 2017) to 0.50 mg Se $kg^{-1}$ (Korol et al. 2013). A popular method of enriching the diet of animals with Se is in–feed administration of selenium–enriched yeast, which is produced with a moderate to high content of this element. Selenium yeast is mainly a source of selenomethionine (Kruzhel et al. 2014), i.e. an organic form with the digestibility level of 70-80% (Rovers 2014). Kruzhel et al.

(2014) concluded that the bioavailability of selenium varies between species of animals. For pigs, this element can be absorbed by the organism in mineral and organic forms. However, mineral selenium compounds in the digestive tract of ruminants are, to a large extent, reduced by bacteria to inassimilable forms, which is due to the low pH in the rumen.

A natural and safe method of the selenium supply to animals may be providing them with a feed having the optimum selenium content, on condition that the level of this element is rigorously controlled in the dry matter. Plants accumulate selenium mainly in the inorganic form, and then synthesise seleno-amino acids in Se-Met, thus becoming a source of its organic form for animals (Lyons et al. 2007).

## SOIL AS A SOURCE OF SELENIUM FOR PLANTS

The basic source of selenium for plants, and consequently for animals and humans, is soil. The content of selenium in the soils worldwide is diverse and dependent on the type of parent rock, the intensity of weathering, leaching and volatilization processes, the soil clay content (mainly the colloidal fraction) and organic matter, and the presence of other elements. The selenium content in soils typically ranges from 0.10 to 2.00 mg Se $kg^{-1}$ (Hartikainen 2005, Borowska et al. 2007, Patorczyk-Pytlik, Kulczycki 2009). Hawkesford and Zhao (2007) state that a selenium content below 0.12 mg $kg^{-1}$ as deficient, within the range of 0.12-0.17 mg $kg^{-1}$ is low, at 0.17-3.00 mg $kg^{-1}$ is medium to high, and above 3.00 mg $kg^{-1}$ becomes excessive.

The problem of selenium deficiency in Poland is associated with the low content of this element in soils and, on the other hand, with significant acidification of the soils. Borowska et al. (2007) determined an average content of 0.14 mg Se $kg^{-1}$ in the soils of the Kuyavia and Pomerania regions, whereas Patorczyk-Pytlik and Kulczycki (2009) reported the average selenium concentration in arable soils around Wroclaw to be 0.20 mg Se $kg^{-1}$. However, it is important that 85% of the soils studied by these authors were characterized by a low selenium content. Dębski (1992) reported that 77% of Poland's soils had a low selenium content in terms of animal nutrition, with the lowest levels in the Kuyavian-Pomeranian region, and this finding implicates a need to enrich soils or fodder with this element. Nowakowska et al. (2015), who researched the selenium distribution in the liver and kidney tissues of deer living in different parts of Poland, found the highest content of this element in the organs of animals from south-eastern Poland, and the lowest – from central and northern part of the country. Because of the strong bond between deer and the environment, the authors claimed that that observations of these animals are an adequate measure of selenium levels in Polish soils. This is consistent with the study of Tomza-Marciniak et al. (2010), who reported a deficiency of selenium in the organs of roe deer from Wielkopolska, another Polish region, and attributed it to the insufficient amount of this element in soil or its low absorption by plants.

Selenium bioavailability and uptake by plants is affected by a number of factors, including the chemical form of this element related to pH and the redox potential, the content of organic matter, clay minerals and iron compounds in the soil, the microbiological activity, fertilization and atmospheric conditions (Lyons et al. 2007, Patorczyk-Pytlik, Kulczycki 2009).

Depending on the pH and the redox potential values, selenium in soil may be present in both organic and mineral forms. The solubility of selenium is a critical factor determining its bioavailability to plants and is not directly related to its total soil content (Lyons et al. 2007). Selenate, Se (VI) – a form soluble and assimilable by plants – is present in alkaline, well-aerated and hydrated soils. In contrast, Selenite, Se (IV), is a predominant form in neutral to acidic, anaerobic and permeable soils. Within the range of pH 3-5, selenite forms insoluble complexes with iron oxides and hydroxides (Fordyce 2013, White 2016).

Higher concentrations of selenium are characteristic for clay soils than for sandy soils (Patorczyk-Pytlik, Kulczycki 2009, Patorczyk-Pytlik, Zimoch 2011). It was found that addition of selenium to organic soil may induce its translocation from the soil solution to the organometallic complexes (Fordyce 2013). This enables retaining selenium in soil, limiting its leaching and increasing the natural abundance of this element, although at the same time it restricts Se availability for plants (Fordyce 2013).

The redox reactions involving selenium in soil may be closely related to the activity of microorganisms, as inorganic selenium compounds accumulate as a result of organic matter decomposition. Bacteria *Bacillus megaterium* have the ability to oxidize elementary selenium to selenite (Fordyce 2013). The microbiological activity may also lead to the formation of volatile dimethylselenide (DMSe), thus resulting in Se losses to the atmosphere (Azaizeh et al. 2003).

Selenates are more mobile in the soil solution, whereas selenites are strongly adsorbed by iron and aluminium oxides and hydroxides, thus being retained in the soil by sorption to the advantage of selenates, as well as other ions, such as sulphate (Fordyce 2013, White 2016). Sulphates may inhibit selenium uptake by plants, mainly in the form of selenates, but the phenomenon is dependent on the S:Se ratio in soil (White et al., 2007, Patorczyk-Pytlik, Zimoch, 2011). Phosphates, on the other hand, may induce the mobilisation of selenium and increase its bioavailability to plants, because $PO_4^{3-}$ ions are quickly adsorbed in soil in exchange for selenates (Fordyce 2013). Such reactions of the ionic antagonism / synergism should be taken into account during soil fertilization of plants with this element.

Plants cultivated in soils with a high selenium content may accumulate significant amounts of this element, which can cause inhibition of their growth and development, and lead to ionic imbalance. Such plants should not be used for the animal nutrition (Płaczek, Patorczyk-Pytlik 2014).

## PROSPECTS OF ENRICHING PLANTS WITH SELENIUM

### Arable land

Plants are the first link in the food chain. Increasing the concentration of selenium in plants is a good way to increase animal and human Se intake, with positive effects on long-term health (Puccineli et al. 2017).

The selenium content in plants is influenced by many factors, such as the abundance and chemical form of this element in soil, the species and varietal properties of plants, climatic conditions, the methods of cultivation and processing of plants (Curtin et al. 2006, Lošák et al. 2009, Broadley et al. 2010). Plants accumulate selenium mainly through the root system in the mineral form as selenate and selenite, and in its organic form as selenocysteine, SeCys and selenometionine, SeMet (White, Broadley 2009).

As reported by Hawkesforda and Zhao (2007), the selenium content in cereals lower than 0.02 mg kg$^{-1}$ DM should be considered as deficient, 0.02-0.04 mg kg$^{-1}$ DM as low, 0.04-0.1 mg kg$^{-1}$ DM as medium to high, and a content exceeding 0.1 mg kg$^{-1}$ D.M. is classified as excessive. In general, when the selenium conent in soil is low, differences between species in the potential to accumulate this element is small; however, plants from the Brassica family, which have a higher demand for sulphur, may contain more selenium even under limiting conditions (White et al. 2007, Puccinelli et al. 2017).

Cereal crops are a very important source of selenium in animal and human diets, and the content of this element in grain is the main determinant of its consumption. According to Lyons et al. (2007), the selenium content in tissues of particular species is arranged in the following order: wheat > rice > corn > barley > oats. Generally, the highest concentrations of selenium in wheat have been reported in the USA and Canada, and in rice – in the USA and India (Zhu et al. 2009).

The content of selenium in European cereal grains lies within the range of 0.02-0.05 mg kg$^{-1}$ DM, while the average concentrations in North America range from 0.20 to 0.50 mg kg$^{-1}$ DM. Finland is an exception because the introduction of selenium to the regular fertilization practise has resulted in an increase of the average Se content from < 0.05 mg kg$^{-1}$ DM in 1985 to 0.16 mg kg$^{-1}$ DM in 2014 (Althfan et al. 2015).

In Poland, little research has been conducted to characterise quantitatively the content of selenium in plants grown in the soils with natural abundance of this element. Sembratowicz and Grela (1997) reported values of: 0.05-0.20, 0.10-0.15, 0.15-0.40, 0.03-0.35 and 0.03-0.30 mg kg$^{-1}$ for wheat, triticale, rye, barley and maize, respectively.

The low content of selenium in fodder crops necessitates enrichment of plants with this element. Previously, Korol et al. (2013) reported that fodders produced for poultry, swine and dairy cows in the animal feed industry in Poland contain amounts of selenium not exceeding the optimum contents. Importantly, the feed mixes studied contained selenium in the mineral form of sodium selenite or sodium selenate characterised by lower bioavailability for animals than the organic forms.

An indirect methods of introducing selenium into the diet of animals and humans is by biofortification, that is enriching plants with this element through plant breeding, genetic engineering and manipulation of agronomic practices (GUPTA, GUPTA 2017).

The problem of selenium deficiency in soils and consequently in the daily diet of humans and animals entered into the scientific debate in the 1970s. Finland became one of the European pioneers of the research when the low Se consumption in the country was found to be a main determinant responsible for increasing the prevalence of the cardiovascular disease (HARTIKAINEN 2005). In 1984, the Finnish Ministry of Agriculture and Forestry decided to implement selenium supplementation with the legal recommendation to incorporate Se in the form of sodium selenate in an amount of 16 mg Se $kg^{-1}$ in fertilizers used for grain production, and 6 mg Se $kg^{-1}$ in fertilizers used for hay and fodder production (EUROLA et al. 1990). The latest regulation of 2012 refers to liquid fertilizers, which may be applied at an amount of 10 g Se $ha^{-1}$ in fertilizers applied to soil and 4 g Se $ha^{-1}$ applied as a foliar fertilizer (ALFTHAN et al. 2015) As a result, the average dietary intake has increased from 0.04 mg Se/day/10 MJ in 1985 to 0.08 mg Se/day/10 MJ, with the latter value being above the present nutrition recommendations. During the selenium fertilization programme, the Se contents determined in spring cereals increased 15-fold compared to the original level, with the mean 6-, 2- and 3-fold increase in beef, pork and milk, respectively (ALFTHAN et al. 2015).

As reported by WHITE et al. (2004), selenium may also accumulate through the use of particular mineral fertilizers, such as ammonium sulphate containing up to 36 mg Se $kg^{-1}$, single superphosphate with up to 25 mg Se $kg^{-1}$, and triple superphosphate incorporating up to 4 mg Se $kg^{-1}$. Natural fertilizers also contain some amounts of selenium. BOROWSKA and KOPER (2006) observed an increase of the selenium content in potato tubers with the increasing application of manure.

There are only few selenium-containing products available in the Polish fertilizer market. Currently, farmers are offered granular fertilizers such as multi-component Yara Mila NPK 23-7-10 (with 0.0015% Se) and Ökophosplus® for grassland (0.00045% Se) from Duka Polska Sp. z o.o. The presence of selenium is also declared by the manufacturer of the plant biostimulant Bio-Algeen S-90.

Plants can be enriched with selenium using the soil and foliar fertilization, as well as the seed pre-treatment. The effectiveness of selenium fertilization may depend not only on the method of application, but also on the dose, chemical form of this element and date of application.

Many studies have suggested that the foliar application of selenium is a more effective method for increasing the Se content in various plant species. Ros et al. (2016), who examined the development of food biofortification strategies in 1960-2014, conclude that after foliar application the average response of crops was nearly twice as strong as the response to soil-applied selenium fertilization. The beneficial effects of increasing the selenium content *via* foliar application have been reported in many plant species, including carrot (Wang et al. 2006), wheat (Curtin et al. 2006, Ducsay, Ložek 2006, Ducsay et al. 2007), maize (Wang et al. 2013), potato (Lošák et al. 2009, Ježek et al. 2011), broccoli (Ghasemi et al. 2016) and tomato (Schiavon et al. 2013). However, the foliar selenium fertilization may pose a higher risk of exceeding the acceptable levels of this element in plants than soil application.

In contrast, Lyons et al. (2004) demonstrated a significantly better effect of soil-applied selenium in wheat cultivation compared to its foliar application. These authors found that soil fertilization with selenium increased its content in wheat grain from 20 to 133 times, depending on a dose applied, whereas foliar application of the same levels of selenium increased its plant content by 6 to 20 times.

The beneficial effect of soil application of selenium on its content in spring wheat grain was reported by Ducsay et al. (2009). The introduction of the highest dose studied (0.20 mg Se $kg^{-1}$) resulted in an increase in the selenium content in grain from 0.04 mg Se $kg^{-1}$ to 0.73 mg Se $kg^{-1}$, with the latter being classified as medium to high according to the classification (Hawkesford, Zhao 2007).

As reported by Curtin et al. (2006), a pre-sowing seed treatment was the least effective method to raise the selenium content in wheat grain. Ros et al. (2016) report that seed enrichment via coating or soaking of seeds could result in responses similar to ones achieved by soil applied fertilizers.

Another factor affecting the efficiency and safety of selenium fertilization is its chemical form and dose used. Most studies so far have confirmed that the form of selenate is more effective, although, owing to the better absorption by plants, this may pose a risk of exceeding the optimum content for animal nutrition. In contrast, Ros et al. (2016) concluded that selenite was on average 33 times more effective than selenate over all treatments and experimental conditions.

Curtin et al. (2006) proposed that a selenium dose ensuring the optimal content of this element in wheat grain should be applied to soil at 4-5 g $ha^{-1}$ when the first node emerges (BBCH 31 phase), whereas in a foliar application it should not exceed 5 g $ha^{-1}$. Ducsay et al. (2007) and Ducsay and Ložek (2006) suggest that a selenium doze of 10 g $ha^{-1}$ is sufficient in foliar fertilization of winter wheat to obtain the optimum level in grain.

Ghasemi et al. (2016) reported that foliar spraying may be an appropriate method to produce Se-enriched broccoli. Based on results from the study on selenium biofortification in the plants cultivated hydroponically, the authors have not found any negative or antagonistic effects on mineral absorption.

When selenium fertilization was studied in potato cultivation, foliar application of 200 and 400 g $ha^{-1}$ was demonstrated to be an effective method to increase the nutritional quality of plants (Lošák et al. 2009). However, as shown by Ježek et al. (2011), the highest dose (400 g $ha^{-1}$) applied to leaves of potato plants may be a stress factor, with its toxic effect responsible for significant modification in the content of specific amino acids.

Another important aspect that should be taken into account when fertilizing plants with selenium is the date of its application. Curtin et al. (2006) compared dates of the treatment (spring and autumn) in wheat, and concluded that soil fertilization with this element should be performed in the spring. According to these authors, significantly lower efficiency of selenium application in autumn is associated with the elution of this element during intensive rainfall, and with elevated conversion of selenate to the less biologically available form of selenite under the high soil moisture. Similar relationships were demonstrated by Broadley et al. (2010) in wheat cultivation.

**Meadows and pastures**

Plants grown in meadows and pastures constitute an important source of nutrients in the animal diet. Filley et al. (2007), investigating the effects of selenium supplementation on the quality of pasture feed, demonstrated that fertilization with sodium selenite at 0.6-2.2 kg $ha^{-1}$ may be a cost-effective method of supplying Se for grazing livestock. The selenium concentrations in plants were moderately high in the first year of the experiment and remained slightly above the nutritional requirements through the second year. However, it was presumed to be in the organic form as selenomethionine, which ensured a much higher margin of safety compared with the inorganic forms. Importantly, the selenium dose applied in the course of this experiment was much higher than proposed, for example, in oilseed rape cultivation by Ducsay and Ložek (2006) < 10 g $ha^{-1}$ Se, or potato by Lošák et al. (2009) 200 g $ha^{-1}$ Se. The major problem of fertilizing meadows and pastures with this element is the risk of exceeding its optimal content in forage plants.

Any selenium fertilization programme for permanent grassland should consider the content of its soluble form in the soil, as well as the conditions affecting its bioavailability for plants. Hambuckers et al. (2010) found that the selenium content in meadow crops in eastern Belgium is below the dietary needs of animals despite the significantly big exchangeable pool of this element in soil, probably in the organic form with low availability to plants. Introduction of fertilization with sodium selenate at 9 g Se $ha^{-1}$ increased its content in meadow plants to the optimum level for animal nutrition, although – according to the authors – the risk of exceeding the recommended content may be significant. As the weather conditions significantly influence Se availability, the selenium concentration in plants could fluctuate yearly due to variation in the mobilization of the selenate pool or in the release of organic Se into phytoavailable forms (Hambuckers et al. 2010).

The selenium content in plants over a long period also depends on the time elapsed since fertilization. As evidenced by Mcdowell et al. (2002), two weeks after the application of 1000 mg Se $ha^{-1}$ its content determined in fescue was 2.42 mg $kg^{-1}$, after 4 weeks it fell to 1.23 mg $kg^{-1}$, after 16 weeks it decreased to 0.28 mg $kg^{-1}$ and after 22 weeks it reached the level optimum for animal nutrition (0.17 mg $kg^{-1}$). The cited authors suggest that the period between the application of selenium in meadows and pastures and the time the plants become suitable for animal feeding is long, and it may be safer to introduce this element during autumn or apply it together with nitrogen fertilization in early spring.

## CONCLUSIONS

Selenium enrichment of animal diets in Poland is currently based on its direct supply in the form of mineral compounds in fodder. Such supplementation may not cover the daily nutritional demand and, on the other hand, the organic forms of selenium present in plants are more assimilable in an animal organism. Selenium biofortification of fodder crops by introduction of this element to the regular fertilization practice, especially in meadows, pastures or forage maize, may be more effective in satisfying the dietary requirements of animals. Due to the small differences between the deficient, optimal and toxic content, it is vital to gain better understanding of how to safely enrich plants with selenium, thus ensuring the optimum level of selenium in the diet of animals and humans.

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